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Engineering Specification

D4 (MBRB) – DIPOLE COOLING SCHEME

Abstract

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5, and 8) and the RF Insertion (IR 4). The D4 twin aperture dipoles are among those utilized in the RF insertions. The D4 dipoles are cooled at 4.5 K. This specification establishes the requirements and interfaces for the cooling of the D4 dipoles.

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History of Changes

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1.0	2001-11-12		Initial submission

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1. OVERVIEW

D4 magnets, along with D3 magnets, are used at IR4 to increase the separation of the beams of the LHC from the nominal spacing of 194 mm to 420 mm so that individual RF cavities can be installed for each beam. The beams are then returned to the nominal 194 mm spacing [1].

Identical to the D2 magnet, D4 is a two-in-one magnet, having two coils in one cold mass similar to the LHC arc magnets [2]. The D4 cold mass has an elliptical cross section with dimensions similar to that of an LHC arc magnet [3]. The D4 cryo-assembly designations are listed in Table 1.

Table 1. Hardware designations for D4 magnet

	D4 (194 mm)
Magnet designation	MBRB
Cryo-assembly	
IR4L	LBRBA
IR4R	LBRBB

1.1 LOCATION

The D4 magnets are installed on each side of IR4 between the Q5 magnet and the DFBM feed box. A sketch of this region is shown in Figure 1. The D4-Q5 combination is treated as a single cryogenic module. Each magnet operates at 4.5 K.

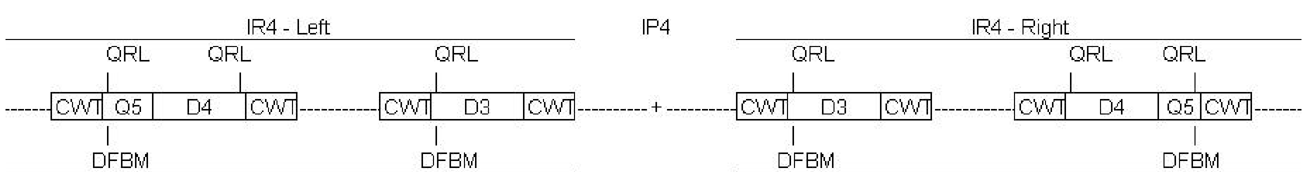


Figure 1. Geometry in the RF Region of the LHC. The nominal 194 mm separation of the beams is increased to 420 mm so that there is space for independent RF acceleration cavities for the two beams.

1.2 COOLING

The D4 and its neighboring Q5 magnet form one cryogenic module with a length of 20 meters. In the D4-Q5 module, each of the magnets, heat shields and the beam screens are cooled in series. Both magnets operate at 4.5K in two-phase helium. Although most of the LHC magnets have to be operated at a temperature of 1.9 K, the D4 magnets can easily provide the necessary field strength for the LHC when operated at 4.5 K. Therefore they have been designed to be operated at 4.5 K to minimize the use of 1.9 K resources.

The cooling scheme utilizes Headers C and D in the LHC cryogenic distribution line to provide a bath of liquid helium at 4.5 K. Header B is not used, which has the advantage of saving electric power in the LHC helium refrigeration system. The lowest temperature of this cooling scheme is 4.5 K due to the 1.3 bar operating pressure of the D Header. The present pool boiling cooling scheme has taken cryogenic module, tunnel slope, magnet geometry and liquid control into consideration. For pool boiling cooling, helium vapor must be vented from the high elevation end of the module. To provide suitable cooling for the long module during cooldown, the helium supply line is connected to the low elevation end opposite to the return line. Thus helium flows through the magnets in one direction during cooldown and warmup.

For steady state operation, liquid helium is fed into the high elevation end to prevent helium vapor, entrained during the Joule-Thomson expansion process, from entering the magnet cold mass. The amount of vapor in the cold mass is limited to that generated from heat in the magnets. The superconducting coil and bus are kept immersed in liquid helium by controlling the liquid level in the end volume of the cold mass.

Beam screens are used to reduce the dynamic heat load to the beam tube and coil. Their use reduces the 4.5 K heat load and the vapor flow inside the magnet cold mass. The beam screens will be provided and installed by CERN.

Two technical service modules, one in each end of the D4-Q5 module, connect the cryogenic module to the LHC distribution line. The purpose is to avoid using a single large connection.

2. CRYOSTAT LAYOUT

The cross sectional view of the LBRB cryo-assembly is shown in Figure 2. The MBRB cold mass, enclosed in an aluminum heat shield, is supported by three posts. These posts are identical to those used in the LHC arc dipole. There are four cold pipes in the cryostat. Only the two heat shield lines, E1/E2, are used for the LHC operation. The cold mass supply lines are used only for tests to be performed at BNL. The inner diameter of these lines is about 5 cm. There is no need to have a beam screen supply line running through the cryostat. The beam screen cooling flow is brought in at the Q5 end, passed down one aperture, turned around at the D4 end, returned back through the other aperture, and taken out at the Q5 end.

E1 and E2 are used to cool the heat shield at 50 K. The inner diameter of these lines is 8 cm but a 15 mm inner diameter line is installed inside one of them to reduce thermal conduction between the heat shield supply side and return lines. The small diameter line merely lies in the bottom of the large diameter extrusion and makes minimal thermal contact.

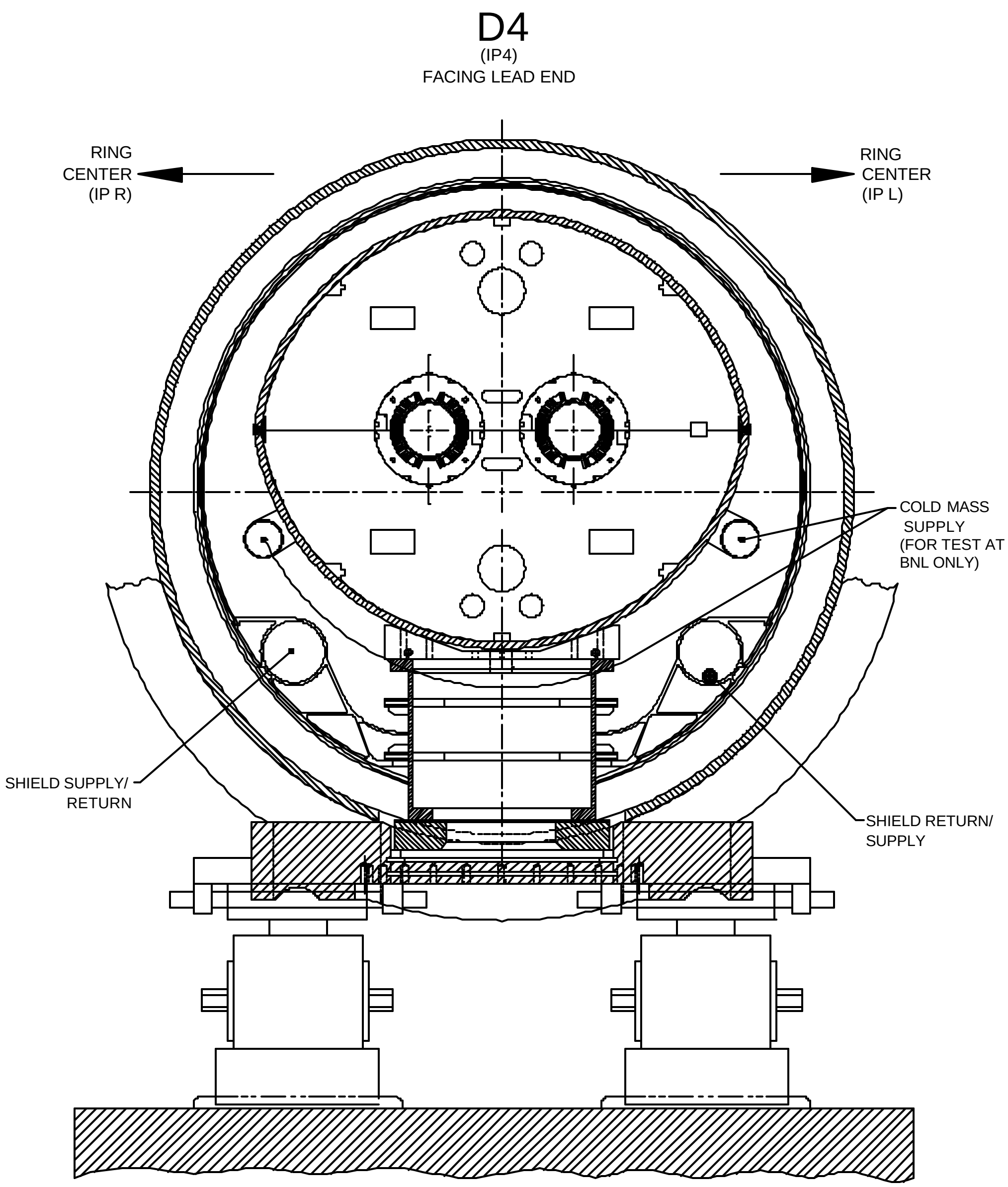


Figure 2 Sectional view of the LBRB (D4) cryo-assembly

3. COOLING

3.1 GENERAL REQUIREMENTS

Heat load is a key parameter for a cooling system. In the LHC, the heat loads consist of two types, static and dynamic. The static heat load comes from conduction through the supports, and radiation past the thermal insulation of the cryostat. The dynamic heat load comes from machine operation. The dynamic heat load consists of synchrotron radiation, imagine currents, beam scattering and photoelectron effects. The beam screen, operated between 4.5 and 20 K, is used to prevent the majority of the dynamic heat loads from entering the 4.5 K magnet. There are three temperature levels of heat load for D4: 50-75 K of the thermal heat shield, 4.5-20 K of the beam screen and 4.5 K of the magnet cold mass.

3.1.1 STATIC HEAT LOADS

Static heat load of D4 is estimated by R. van Weelderen of CERN [4] and is given in Table 2. Heat loads for resistive heating of electrical splices and conduction through instrumentation feed throughs, cold to warm transitions, QQS and cryogenic jumper lines are also included in Table 2.

Table 2. Design Static heat load (Watts) for a D4 magnet

Source	***Heat Shield*** ***50-75 K***	***Beam Screen*** ***4.5-20 K***	***Cold Mass*** ***4.5 K***
Supports	21.30	-	1.50
Thermal Shield (50-75	28.08	-	-
Radiation to cold mass	-	-	1.02
Resistive heating	0.01	-	0.31
Instrument feed	-	-	0.53
Cold to warm transition	12.00		5.45
QQS	3.70		0.09
½ jumper	0	-	0.54
Total	65.09	0	9.43

3.1.2 DYNAMIC HEAT LOADS

The dynamic heat load is developed inside the beam tube. It does not reach the 50-75 K heat shield. An actively cooled beam screen is used to remove most of the dynamic heat loads that would otherwise be deposited in the 4.5 K magnet. The dynamic heat loads of D4 are estimated by CERN [4] for both the nominal and ultimate LHC operating conditions, and are given in Table 3. The heat loads for synchrotron radiation, image currents, beam scattering and photoelectrons are given in watts per meter. The photoelectron heat input depends on whether the region has magnetic field. A total length of 10.40 m is used in the dynamic heat load calculation with 9.45 m of that assumed to be the field region.

Table 3. Dynamic heat load of D4 at nominal and ultimate operating conditions

Source	***Beam Screen Nominal***	***Cold Mass Nominal***	***Beam Screen Ultimate***	***Cold Mass Ultimate***
Synchrotron radiation	0.200	0	0.302	0
Image Current (W/m)	0.192	0.005	0.438	0.011
Beam gas scattering (W/m)	0	0.050	0	0.050
Photoelectron[a]				
-field region (W/m)	0.241	0	0.830	0
-field free region (W/m)	2.079	0	7.140	0
Total for 10.40 meter	8.33	0.57	22.32	0.63

Note: (a) From the mechanical layout drawings [6], the field region is taken as the magnetic length 9.45m. The total length is taken as the cold mass length 10.40 m. Their difference is taken as the field free region 0.95 m.

3.1.3 TOTAL HEAT LOADS

Total heat load is the sum of static and dynamic heat load and is given in Table 4. The cooling system is designed for the maximum expected heat load of the D4 and Q5. Pressure and temperature at the 4.5 K supply line are expected to be 3 bar and 4.6 K. Pressure in the return line D during normal operation is not expected to be greater than 1.3 bar.

Table 4. Total heat load (Watts) for the D4 magnets at nominal and ultimate luminosity

	Heat Shield 50-75 K	Beam Screen 4.5-20 K	Cold Mass 4.5 K
Nominal			
Static (Table 1)	65.1	-	9.43
Dynamic (Table 2)	-	8.3	0.57
Total	65.1	8.3	10.0
Ultimate			
Static (Table 1)	65.1	-	9.43
Dynamic (Table 2)	0	22.3	0.63
Total	65.1	22.3	10.1

3.2 COOLING SCHEME

The D4 and Q5 magnets are combined together in one cryogenic module. The module is cooled by pool boiling of liquid helium at 4.5 K. The helium flows associated with pool boiling cooling are sensitive to the tunnel slope and the feed and return lines have been arranged to produce the correct flow directions. The –0.36% slope at IR4 results in a –7.2 cm elevation change over the 20 m length of the module. The cryogenic feed is located at the high elevation end of the module and is connected to the LHC distribution line through the technical service module QQS.

The flow schematics for the left and right sides of IR4 are given in Figures 3 and 4. The dashed box, around D4 including the QQS on the D4 side, indicates the responsibility of BNL. The CERN piping and valve conventions [5] are given inside the brackets, []:

- CL1 [CL] is the cooldown line
- CL2 [CL] is the steady state liquid feed
- LD [LD] is the vapor return
- E1/E2 [FF/EE] are heat shield cooling
- CFV, LCV and TCV are control valves for cooldown, steady state and flow respectively.

3.3 OPERATION AT 4.5 K

For the 4.5 K steady state operation, two phase helium from Header C is fed to the high elevation end of the D4-Q5 cryogenic module and returns as vapor from the same end. Liquid level is controlled by valves LCV1 [CV931]. The level gauges are installed in the end volume of the cold masses.

On the left side of IR4 (see Figure 3), where the Q5 is higher than D4, two phase helium from Header C is fed to the high elevation end of Q5 through line CL2 [CL]. Helium vapor returns to Header D from the high elevation end of Q5 through line LD [LD]. A liquid level gauge, installed in end volume of the Q5 cold mass, provides a control signal for valve LCV1 [CV931].

On the right side of IR4 (see Figure 4), where D4 is higher than Q5, two phase helium from Header C is fed to the high elevation end of D4 through line CL2 [CL]. Helium vapor returns to Header D from the high elevation end of D4 through line LD [LD]. A liquid level gauge, installed in the end volume of the D4 cold mass, provides a control signal for valve LCV1 [CV931].

3.4 HEAT SHIELD COOLING

The heat shield cooling flow enters the cryogenic module from the QQS on the D4 side through line E2 [EE] (see Figures 3 and 4). Helium flows through the supply line E2 to Q5 end of the module where it turns around and returns through the E1 line to cool the heat shield. The shield flow returns to Header F through the [FF] line.

3.5 COOLDOWN FROM 300 - 4.5 K

For the cooldown from 300 K to 4.5 K, helium enters the D4-Q5 module from the low elevation end. It exits the module from the high elevation end. The CERN piping and valve convention is given inside the brackets, [].

On the left side of IR4 (see Figure 3), helium from Header C flows through jumper line [CL], control valve CFV [CV920] and line CL1, to the low elevation end of D4. It flows through D4 and into Q5. Helium returns to Header D from the high elevation end of Q5 through line LD [LD].

On the right side of IR4 (see Figure 4), helium from Header C flows through jumper line [CL], control valve CFV [CV920] and line CL1, to the low elevation end of Q5. It flows through Q5 and into D4. Helium returns to Header D from the high elevation end of D4 through line LD [LD].

3.6 BEAM SCREEN COOLING

The two beam tubes of D4-Q5 are cooled in series. The beam screen cooling flow enters the D4-Q5 module from the QQS in the Q5 side through line CC' [CC']. It flows through two cooling passages inside one of the beam tubes to the non-lead end of D4. After cooling this beam tube, the helium flow turns around. It flows through two cooling passages in the 2nd beam tube toward Q5. The flow exits the D4-Q5 module from the same QQS in the Q5 side through line C'D [KD]. A temperature control valve, TCV [CV947], is used to maintain the screen below 20 K.

3.7 SAFETY RELIEF VALVE

No relief valve is allocated for the D4-Q5 cryogenic module. There is no relief valve between the beam screen and Header C in the LHC distribution line. The relief valve in Header C is used to vent helium in the 4.5-20 K cooling line. There is no relief valve between the D4-Q5 cold mass and Header D either. Two phase helium in the D2-Q4 cold mass will be vented to the Header D should the pressure build up. The 50-75 K cooling circuit of the D4-Q5 module is part of the LHC sector heat shield which has relief valves to handle the venting capacity of the entire circuit. The vacuum vessel tank relief will be provided on the Q5 cryostat.

3.8 CONTROL VALVES

The control valves shown in Figures 3 and 4 are sized for operating and cooldown conditions. Since the heat shield of D4 is in series with Q5, the required helium flow and control valve TCV is calculated from the total heat load of the D4-Q5 cryogenic module.

3.9 OTHER INSTRUMENTATION

For convenience of cryogenic operation, redundant temperature sensors will be installed in the middle of the D4 cold mass. An electric heater will be installed inside the end volume in the lead end of D4.

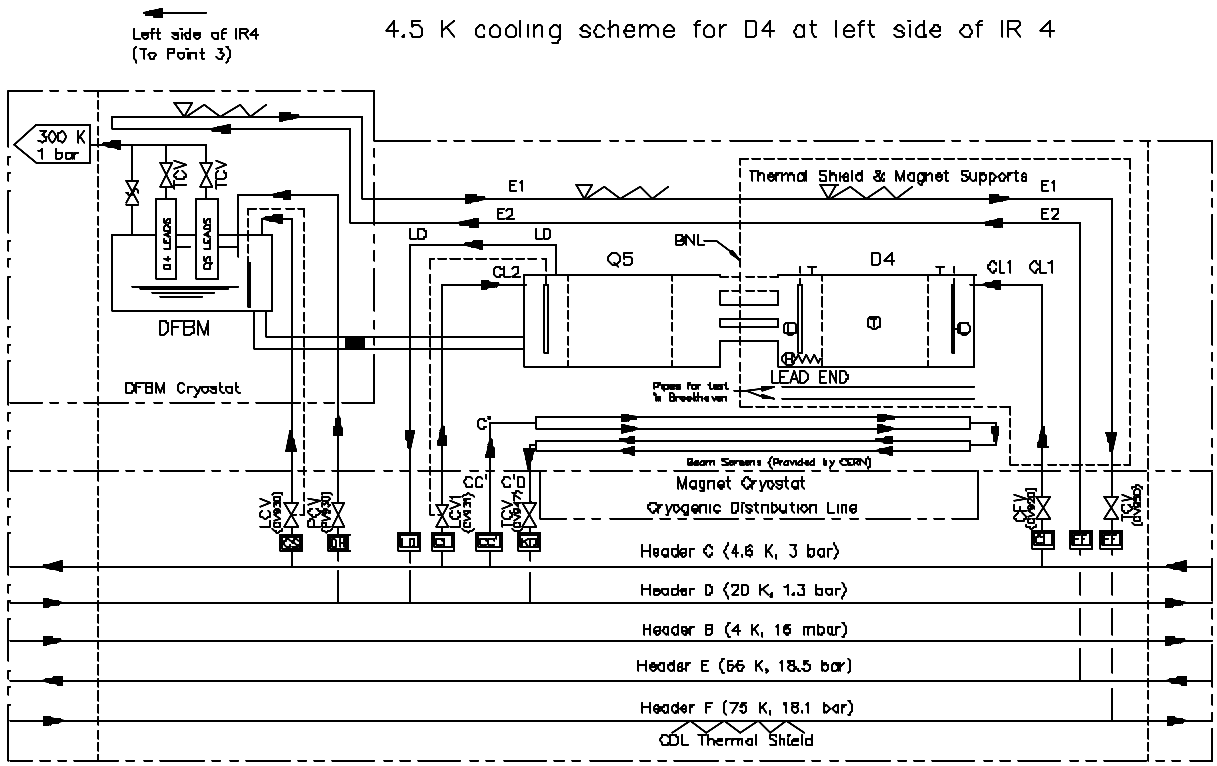
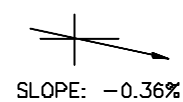


Figure 3 4.5 K cooling scheme for D4 at the left side of IR 4



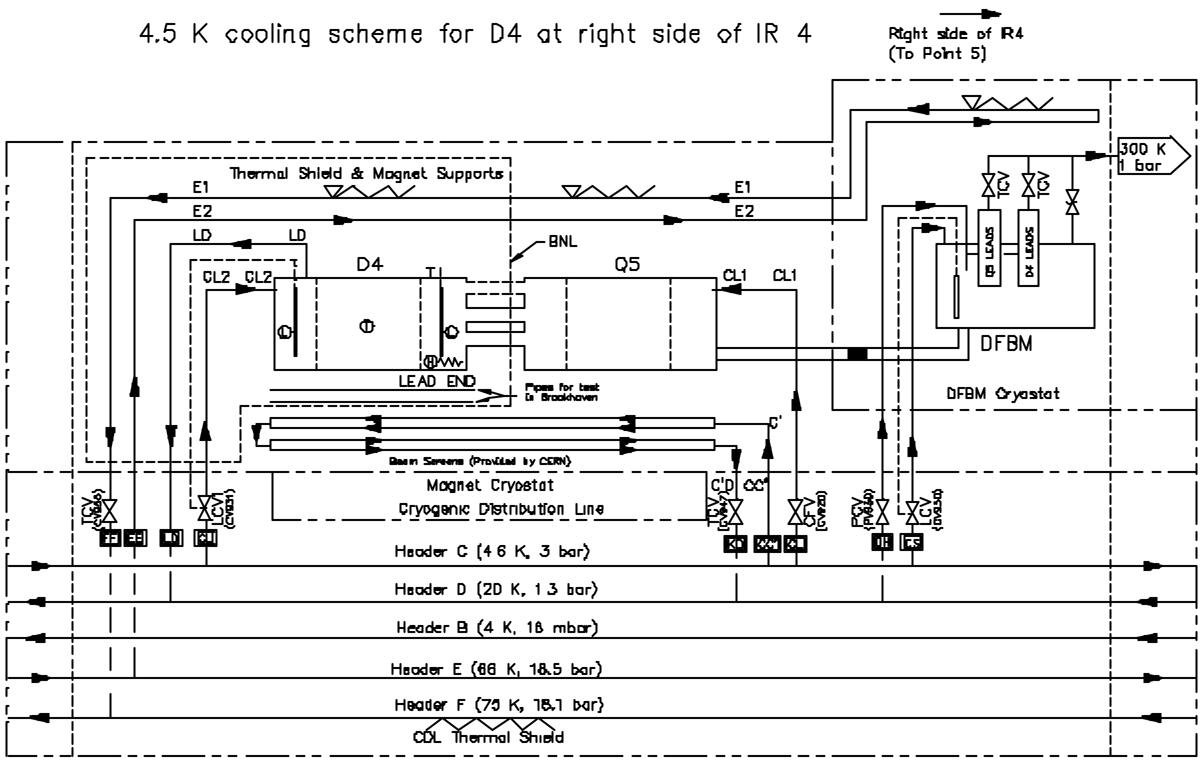
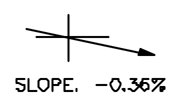


Figure 4 4.5 K cooling scheme for D4 on the right side of IR 4



4. REFERENCES

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5. "Various LSS QRL Jumper Interface Piping", R. vanWelderen, http://vanweeld.home.cern.ch/vanweeld/insertions/piping/jumperpiping.html, version 1.0, 1 July 2001.